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Evaluation of options for energy recovery from municipal solid waste in India using the hierarchical analytical network process

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ABSTRACT

In this paper a Hierarchical Analytical Network Process (HANP) model is demonstrated for evaluating alternative technologies for generating electricity from MSW in India. The technological alternatives and evaluation criteria for the HANP study are characterised by reviewing the literature and consulting experts in the field of waste management. Technologies reviewed in the context of India include landfill, anaerobic digestion, incineration, pelletisation and gasification. To investigate the sensitivity of the result, we examine variations in expert opinions and carry out an Analytical Hierarchy Process (AHP) analysis for comparison. We find that anaerobic digestion is the preferred technology for generating electricity from MSW in India. Gasification is indicated as the preferred technology in an AHP model due to the exclusion of criteria dependencies and in an HANP analysis when placing a high priority on net output and retention time. We conclude that HANP successfully provides a structured framework for recommending which technologies to pursue in India, and the adoption of such tools is critical at a time when key investments in infrastructure are being made. Therefore the presented methodology is thought to have a wider potential for investors, policy makers, researchers and plant developers in India and elsewhere.

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1. Introduction

Rapid development in India has led to severe problems with managing Municipal Solid Waste (MSW). The management of MSW is complex due to its variable composition, which depends on local demographic and their habits. In developing countries such as India, MSW's complex nature is exacerbated by the fact that additional waste streams from industries, agriculture and hospitals often end up being combined in the solid waste mix. While rapid population growth and urbanisation have resulted in increasing demands for energy services, several areas of rural India still remain un-electrified and even those areas with access to electricity may still suffer from regular blackouts.

In 2006, India produced 90 million tonnes of solid waste and this is expected to increase to 300 million tonnes per annum by 2047 [1]. Despite the introduction in 2000 of the MSW Management and Handling Rules, the collection efficiency of MSW in India is still only about 70% and waste is primarily disposed of through dumping and landfill, around 90% of which is unsatisfactory [2,3]. Some regions even have no collection procedures in place at all due to inhabitants being unwilling or unable to pay. This has given rise to numerous social and environmental issues including pollution from heavy metals, land usage, hazardous and infectious wastes, and leachate and air pollutants as landfill sites usually lack gas monitoring and collection systems [4]. Thus there is an urgent requirement to improve waste prevention and segregation, and to increase MSW energy recovery projects that reduce waste mass and volume, alleviate health hazards from pollution, and provide valuable energy services.

In Europe around 40 million tonnes of MSW is incinerated a year for thermal and electrical generation, 130 million tonnes of MSW is combusted annually worldwide [5]. The estimated potential for energy recovery from MSW in India is 1700 MW; however in 2009 projects totalled a mere 34 MW [6]. India's primary energy consumption mix in 2010 consisted of coal (52.96%), Oil (29.66), natural gas (10.63%), hydro-electric (4.81%), nuclear (0.99%) and renewables (0.95%) [7]. With a poor renewable energy contribution and a heavy reliance on fossil fuel imports, which are rapidly increasing in price, India faces growing concerns over its energy security and sustainability [8]. The MSW composition and

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generation per capita for a variety of regions of India have been report in the literature [9–12]. The problem for India is that the composition of MSW has a higher moisture and organic fraction than in western countries, making conventional waste-to-energy (incineration) plants unsuitable [13]. There are however many established and emerging energy recovery technologies which are being promoted by municipal authorities. Technologies include incineration, anaerobic digestion (AD), landfill gas, pyrolysis and gasification. Some of these technologies are the subject of considerable R&D spurred also by increasing use of biomass for energy. Downstream there are also many uses for the energy outputs e.g. electricity, combined heat and power, tri-generation and waste-derived fuels. To encourage the development of MSW recovery projects in India a number of subsidies and additional incentives are now in place [14]. The market share for MSW treatment and disposal technologies in India in 1997 was 50% composting, 30% anaerobic digestion, 10% pelletisation and 10% sanitary landfill [15]. However in 2003 it was reported that 315 MW of power generation from the gasification of MSW was under development [16].

As the technological alternatives for generating electricity from MSW grow in number and complexity, so are the strategic decisions required for the effective evaluation and management of these sustainable energy schemes. As a result, Multi-Criteria Decision-Making (MCDM) methods are becoming popular tools to use in sustainable energy planning and environmental decision making, as reviewed in Refs. [17–19]. These tools are already well established in the traditional energy sector [20].

Structured decision-making methods have been used in the field of waste management by a number of authors. Galante et al. [21] used a fuzzy goal programming and multi-objective approach for the design of an integrated solid waste management system in Palermo, Italy. Goal programming has also been used to optimise the management of computer waste flow streams in India, a growing issue in developing countries [22]. Minciardi et al. [23] developed a non linear multi-objective model to optimise the flow of waste to alternative treatment plants in Genova. Contreras et al. [24] used the Analytical Hierarchy Process (AHP) to select between different waste management plans to implement in Boston, USA. Similarly, Hokkanen et al. used ELECTRE to choose between solid waste management schemes in Finland [25]. Multi-criteria methods such as the AHP have also been integrated with Geographical Information Systems (GIS) for the site selection of landfills and waste management facilities [26,27].

The AHP, developed by Saaty [28], is the most popular MCDM technique and has been widely adopted for technology evaluation and selection in the renewable energy sector [29–31]. Another emerging decision-making method is the Analytical Network Process (ANP), which is an extension of the AHP to consider interdependencies between decision attributes, thus improving the accurate modelling of complex decisions. The ANP was also developed by Saaty and is described in detail in Ref. [32]. Sipahi and Timor [33] give an overview of applications of the AHP and ANP. They predict that ANP will grow in popularity as the benefit of the network approach becomes better understood for dealing with real world situations, especially in developing countries. Wolfslehner et al. [34] compared the AHP and ANP processes for the selection of a sustainable forest management scheme; they also highlighted the advantage of ANP in strategic decision making. Several authors have also adopted a Hierarchical Analytical Network Process (HANP) model [35–37] and introduced advanced fuzzy logic [38]. While these approaches add additional complexity to an analysis, they improve the reliability of subjective information which can otherwise be uncertain or vague.

The ANP has indeed grown in popularity in recent years being used for a variety of applications in the field of sustainability and has been validated in numerous market-share case examples [32]. Meade and Presley [39] used the ANP to select between alternative environmental R&D projects. Erdoğmuş et al. [40] and Köne and Büke [41] used the ANP to select between alternative fuels for domestic heating and electricity generation in Turkey. Atmaca and Basar [42] and Ulutaş [43] applied ANP using the software Super-Decisions for selecting a power source for Turkey. In the field of waste management, ANP has been utilised for evaluating alternative countermeasures for site remediation [44] and for landfill site selection [45]. Khan and Faisal [46] used the ANP to evaluate three alternative integrated waste disposal scenarios for India by considering landfill, composting and incineration.

Nevertheless, there are a number of additional options for disposing of MSW and generating electricity in India, which have not been adequately researched. Therefore the aim of this study is to demonstrate the use of an HANP method for systematically evaluating alternative technologies for generating electricity from MSW, and thus make a contribution to the effective management of waste and provision of energy services in India. Specific objectives of the study are to review the status of the technological alternatives in India, outline suitable evaluation criteria, and carry out and examine an ANP study to identify the preferred technologies for generating electricity from MSW.

The methodology developed to achieve these objectives is outlined in the following section. In Section 3 a short technology review is provided on bio-energy conversion technologies for generating electricity from MSW. Section 4 provides details on an HANP analysis that has been conducted to evaluate and rank these alternative technologies. In Section 5 a sensitivity study is performed to examine the HANP results. Section 6 compares the findings from the HANP with those obtained from an AHP analysis. These results are then discussed and recommendations are made for energy recovery from MSW in India and further works using HANP in the energy sector.

2. Methodology

This study adopts both primary and secondary research methods. A structured literature review is carried out to characterise the technology options for generating electricity from MSW in India. An output of the review is a shortlist of technology alternatives and elevation criteria (grouped into clusters of technical, financial, environmental and risk). To establish subjective priority weightings for the criteria, a questionnaire is developed and delivered to five participating experts working within the Mumbai, Nagpur and West Bengal Municipal Corporations, Jadavpur University and the Government of West Bengal, Municipal Affairs Department. An HANP analysis is then completed using Super-Decisions® (Creative Decision Foundation, USA), a software tool for performing ANP/AHP decision studies. Pair-wise comparisons are performed using a combination of the literature review and questionnaire results. As an output, a ranking order of preference is established for the alternative technologies. To examine the sensitivity of the result, the criteria weighting are varied to determine potential changes in the ranking order. Variations among different MCDM methods are also investigated be conducting an AHP analysis for comparison.

3. Technology review

The purpose of this review is to assess the main technologies applicable to energy recovery from MSW and to research factual information relating to their use in India (units are presented in US dollars, converted from Indian Rupees (INR) at a rate of 0.018). Technologies for generating energy from biomass fall into two categories, biochemical and thermochemical conversion. The biochemical processes (anaerobic digestion and landfill) involve decomposition by microorganisms to produce biogas, which can be upgraded to biomethane or hydrogen. Ethanol and butanol can also be recovered during fermentation. Wastes with high moisture and bio-degradable content aid microbial activity and are thus preferable for biochemical conversion. The thermochemical conversion processes (gasification, pyrolysis and incineration) use thermal decomposition for producing heat, gas or oil. Thermochemical conversion is useful for dry wastes with a high percentage of non-biodegradable matter. From these different processes, electricity can be generated through the use of product recovered bio-fuels, a gas turbine, an internal combustion engine or a boiler-steam turbine. Product recovered bio-fuels can include gasoline, biodiesels, methanol, ethanol, mixed alcohols and hydrogen. Presently, MSW is not widely used for producing bio-fuels as biogas is primarily used for heat and power [47].

The biochemical and thermochemical technologies now reviewed include anaerobic digestion, landfill with gas recovery, gasification, conventional incineration and pelletisation. The use of bio-fuels and pyrolysis for generating electricity from MSW in India are not considered due to the paucity of information.

3.1. *Anaerobic digestion*

Anaerobic digestion (AD) is a biochemical process producing biogas through the biodegradation of organic material in the absence of oxygen with anaerobic microorganisms. The process typically involves pre-treatment, separation of non-digestible materials, shredding, digestion, biogas recovery and residue treatment. Inside a digester, feed waste is usually diluted with water, sewage sludge or re-circulated digester effluent. Around 1 million tonnes of organic MSW is treated by AD worldwide, and plants operate with either single or multi stages under thermophilic (50–65 °C) or mesophilic (20–40 °C) conditions [48]. The temperature controls the residence times, which for thermophilic and mesophilic are about 15 and 30 days respectively. Anaerobic digestion is often used to pre-treat the Organic Fraction of MSW (OFMSW) before it is sent to landfill, thus reducing mass, and methane and leachate emissions. In AD the OFMSW volume is reduced by around 70%, therefore, assuming a 50% organic fraction, the total MSW volume is reduced by around 35% [49].

Biogas released during anaerobic digestion (comprising largely of methane, 55–60%, and carbon dioxide, 30–45%) is scrubbed to improve gas quality and can then be used directly as a fuel for power generation, and has an energy content of 20–25 MJ/m^3. Typically around 100–350 m^3 of biogas per tonne of OFMSW can be produced [16,50]. Compost can also be obtained from aerobically cured bio-solids. A pilot plant in India developed by Western Paques demonstrated that 150 tonnes OFMSW per day resulted in 14,000 m^3 of biogas, enough to generate 1.2 MW of power. Considering the entire AD system the net electricity output will be around 100–150 kWh/tonne OFMSW, in comparison, standard composting uses 30–35 kWh/t [50,51]. In controlled AD 1 tonne of OFMSW produces 2–4 times more methane than landfill does in 6–7 years. The cost of generating electricity from MSW using AD in India has been estimated to be around 0.05 $/kWh [52]. For plant capacities of 5000–100,000 tonnes per annum (tpa) the capital cost ranges considerably from 242 to 1212 $/tpa, and running costs range from 18 to 50 $/t [51]. Parasitic loads are relatively high for AD at around 20–40% [50,51]. Estimations for the CO_2 emissions from electricity generated from AD are 0.2 kg CO_2/kWh$_e$ [51]. In terms of environmental impact, AD's global warming potential is low in comparison to incineration, composting and landfill [53]. The addition of sewage waste to MSW (optimal mixture around 25% MSW to 75% sewage sludge [54]) for AD has been shown to enhance biogas production [55]. However this is beyond the scope of this review.

3.2. *Landfill*

Landfill Gas (LFG), which consists primarily of methane and carbon dioxide, occurs in waste disposal sites through anaerobic decomposition of biodegradable MSW. Annual LFG emission rates initially increase in landfill sites before decreasing after several years, therefore at a certain point it becomes economically unfeasible to continue utilising produced LFG. Though landfill sites are prevalent in India and elsewhere in the world, compact levelling, covering and gas collection are practices rarely observed in India [9]. As a result, pockets of LFG build in pressure and thus explosions and fires are a concern. Leachate, which is a concentration of toxic substances, can also escape as water enters a landfill and leaks due to damaged liners or a lack of liners entirely, contaminating ground water. Waste in tropical countries has been evaluated to yield 450 m^3 of landfill gas per tonne of MSW [56]. Well designed landfills capture around 50–75% of produced LFG, total lifetime gas recovered from a site will be around 35% [57]. Therefore captured LFG will be around 157 m^3/t of MSW [56]. Collection efficiencies are significantly lower (20–35%) at sites that have an absence of base liners, no top covering and leaks in the periphery [58].

Landfill gas has a heat content of around 18 MJ/m^3, therefore, assuming an internal combustion engine efficiency of 35%, a parasitic load of 2% and a generator efficiency of 80%, the electrical energy recovery potential of landfilled MSW is around 215 kWh$_e$/t [57,59]. An economic study of a landfill system for methane collection in Mumbai by Indira Gandhi Institute of Development Research found the cost of MSW disposal to fall from 73 $/t to a range of 4–10 $/t with the system producing a total methane and manure value of 3.6 and 0.2 million dollars per annum respectively [56]. The current methane emissions from landfill sites in India have been reported to range from 146 to 454 mg/m^2/h [60]. Emissions from producing electricity from LFG are estimated to range from 1 to 1.2 kg CO_2/kWh$_e$ [61]. Electrical output per land usage is around 4.98 MJ/m^2 a [62]. Landfill gas recovery plants are typically expensive with a capital cost of around 15,000 $/kW [63]. Estimated operating costs and cost of electricity generated range respectively from 61 to 115 $/kW/year and 8–15 ¢/kWh [64].

3.3. *Gasification*

Gasification involves the partial combustion of biomass to generate gas and can be achieved for MSW after shredding to reduce particulate size [65]. Several types of waste cannot be treated by gasification without pre-treatment, however agricultural, plastic and wood wastes can be. India has one of the world's largest small gasifier programmes and 100% producer gas systems are now commercially available from a number of manufactures and range in scale from a few kWs to MWs. As of September 2009 India had a totalled installed biomass gasifier capacity of 243 MW [8]. The cost of gasifiers range from 180 to 270 $/kWh for thermal applications and 540–810 $/kW$_e$ for mechanical and electrical generation systems. For small gasifier plants in India (20–1000 kW$_e$), capital costs are higher at around 900–1200 $/kW$_e$ [66]. Generation costs are around 0.05–0.07 $/kWh$_e$ [67,68]. A gasification-steam cycle is the simplest option for energy recovery as the gas does not require pre-treatment. The producer gas has a heating value of 15–20 MJ/N m^3 and net electrical efficiencies of 23–25% are achievable [65]. For electricity production using gasification, the parasitic electrical demand is around 20% and carbon dioxide emissions are around 114 g CO_2/kWh$_e$, in comparison, incineration results in 220 g CO_2/kWh$_e$ [51]. Gasification reduces volume by up to 90% with virtually zero hazardous emissions [63]. Operations and maintenance costs for gasification systems are high due to tar and volatile gases damaging gas engines, which is the major drawback of gasification. Regular maintenance of the cleaning system is therefore required [63]. Operations and maintenance costs of some different gasification systems, reported by the National Renewable Energy Laboratory (NREL), varied from 65 to 112 $/t. Net powers and parasitic loads ranged from 643 to 901 kWh/t and 13–28% respectively [69]. Pyrolysis is an indirect gasification process with inhert gases and can produce liquid, solid and gasous fuels from MSW as well as reducing volume by 50–90%. The composition of the pyrolysis gas from MSW is given in Ref. [3]. Electricity generation from pyrolysis is expected to cost in the region of 0.07 $/kWhe when co-firing [70]. However, pyrolysis is not widely established for electricity generation in India or elsewhere and is therefore excluded from this study.

3.4. *Incineration and pelletisation*

Used in many countries, waste incineration can reduce MSW mass and volume by 70% and 90% respectively as well as providing steam for electricity production and co-generation. The net electrical efficiencies and capital costs of European incineration plants are around 15% and 700–1300 $/tpa (560–1030 Euros/tpa) [51]. Parasitic loads are also reported to be around 15%. By-product emissions contain pollutants, however these quantities are small after secondary treatments such as after burning, scrubbing or filtration [4]. The product left is bottom ash and some fly ash, which is disposed of mainly in landfills. Incineration of MSW in India is not widely adopted due to a high organic content (40–60%, increasing in rural regions), high moisture content, high inert content (30–50%) and low calorific value (3.3 and 4.2 MJ/kg) [2]. A conventional incineration system with a net electrical efficiency of 15% would therefore have a net electrical output of 167 kWh/t MSW. Direct combustion projects are therefore generally regarded as economically unfeasible in India [11]. The typical cost of waste-to-energy plants in India ranges from 870 to 1780 $/kW (5–10 Crore/MW) [71].

Pelletisation of MSW has proven to be a successful alternative to direct combustion. A 6.6 MW power plant project using MSW pellets was commission in 2003 in Hyderabad at a cost of 7.7 million US dollars [72]. The pellets were reported to have a heating value of 14.65 MJ/kg and could produce 1.22 kWh/kg of electricity. With 20% of the treated MSW turned into pellets, the electrical output would be 244 kWh/tonne of MSW or 1220 kWh/tonne of pellets [73]. Power plants using pelletisation require around 1 hectare/MW and in 1996 were reported to cost 800–850 $/kW [63]. The capital and operating costs of producing pellets from biomass in north America were reported to be 6 and 45 $/t respectively, however it would be less in India [74]. A pilot MSW pelletisation plant initiated in Mumbai by the Department of Science and Technology (Government of India) found that 0.381 kg of CO_2/kg steam was generated from a boiler with an efficiency of 53% (similar to coal emissions), which is around 1.3 kg of CO_2/kWh, assuming a cycle efficiency of 30% and a steam enthalpy of 3500 kJ/kg. It was claimed that the steam generation costs were around 6 $/t, i.e. 0.025 $/kWh$_e$, which is lower than a coal power plant [75]. Land usage of the pilot plant was 0.8–1.6 hectare per 100 tonnes per day of fuel pellets [75].

3.5. *Output of literature review*

The main technological alternatives for generating electricity from MSW in India have been identified as anaerobic digestion (AD), landfill with gas recovery, gasification, conventional incineration and pelletisation (incineration of pellets). As a result of the information collected in Sections 3.1–3.4, the evaluation criteria deemed necessary to compare these alternatives falls into four categories of technical, financial, environmental and risk, as summarised in Table 1. These criteria are comparable to those used by other authors in similar studies [18,25,29,42,45].

Table 1
Characteristic table of technological alternatives for electricity generation from municipal solid waste in India.

	Description	Units	Landfill	Anaerobic digestion	Incineration		Gasification
			Gas recovery	MSW only	Conventional	Pellets	
Technical							
Energy content of fuel	Treatment/feed pumps	MJ/m^3	15–21	20–25	3.3–4.2	15	15–20
Net electrical output		kWh/t MSW	215	100–150 OFMSW	167	244 (1220 PTP)	643–901
Parasitic loads		%	2–5	30–40	15%	>15%	20
Retention time		times	Years	15–40 days	Minutes	Minutes	Minutes
Pre-treatment		–	None	Segregation/Shredding	None	Pelletisation	Segregation/Shredding
Financial							
Capital cost	Initial cost of facility	$/kW	15000	*[a]	890–1780	867–1175	445–534
		$/tpa	*	242–1212	679–1248	685–1254	635
Generation cost		$/kWh$_e$	0.08–0.15	0.05	0.07–0.13	0.025	0.05–0.07
O&M costs	% of capital cost/year	%	0.4–0.7	4–7.5	6.5–7.5	*	11.5
		$/tonne	*	18–50	34–82	79–127	65–112
Environmental							
Emissions	CO_2 tons eq.	CO_2/t MSW	1.97	1.19–1.42 (wet–dry)	1.67	*	Low
		kg CO_2/kWh	1–1.2	−7.5 to 0.198	0.22	1.3	0.11
Volume reduction of MSW		%	Low/slow	40–75% OFMSW	90	18	50–90
Risk							
Market establishment	In India	%	10	30	0	10	0
	Worldwide	million t/year	*	1 OFMSW	130		*

[a] Cells represented with a '*' indicate where data could not be found.

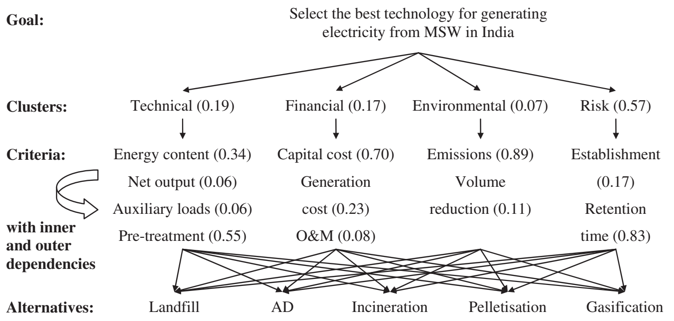

Fig. 1. Hierarchical ANP framework for selecting the best technology for generating electricity from MSW.

4. The HANP analysis

In a hierarchical analytical network process study, a network of clusters (alternatives, technical, financial, environmental and risk) with internal elements (criteria) is structured within a hierarchy. Using the data gathered from the literature review (see Table 1), the alternatives are pair-wise compared with respect to each criterion. Preference is scored on a scale of 1–9, 1 equally preferred, 9 extremely preferred. Priority weightings for the individual clusters and criteria are established by pair-wise comparison with respect to a goal; which in this study is to select the best technology for generating electricity from MSW in India. To develop the weightings, 5 experts working in the waste management sector in India have been consulted. This includes principal scientists, an executive engineer, an academic and a head of department working within the Mumbai, Nagpur and West Bengal Municipal Corporations, Jadavpur University and the Government of West Bengal, Municipal Affairs Department. Through the use of questionnaires, the experts have been given the opportunity to rank the importance of the clusters and criteria with respect to the goal. Average cluster and criteria preferences have then been used to complete the pair-wise comparison matrix and a suitable level of consistency has been achieved. Fig. 1 delineates the framework used in this study and the resulting priorities established by the experts.

Inner and outer dependency weightings for the criteria are assigned by asking the following question: with respect to a given parent element, and bearing in mind the overall goal of selecting the best technology generating electricity from MSW in India, which of two elements has the greatest influence on the parent element. The dependencies considered in this analysis are in the technical and financial clusters as criteria such as net output and generation cost are dependant on other criteria.

The analysis is completed with the help of the software, SuperDecisions, a well established package that has been used for ANP and AHP analyses by a number of authors [42,43,45]. Results for the weighted and limit supermatrix are shown in Tables 2 and 3. The supermatrix is a two-dimensional matrix representing all the priority vectors developed from pair-wise comparisons. A weighted supermatrix includes the criteria weightings. A limiting supermatrix provides the final priority ranking of each alternative and is developed by raising the matrix to powers to reach convergence. The final results for the analysis are shown in Fig. 2.

With a priority ranking of 24%, the HANP analysis indicates that AD is the preferred technology for generating electricity from MSW in India. Gasification is second with a normalised priority of 23%. Landfill is found to be the least preferred technology with a ranking of 12%. However, given the close ranking of AD and Gasification, this ranking order may differ depending on which experts or stakeholders are consulted for a specific study or which MCDM method is adopted.

5. Sensitivity study

To investigate the sensitivity of the result, the priority weightings are varied to determine potential changes in the ranking order of the alternatives. We find that depending on the assigned weightings, AD, gasification or incineration may rank as the most preferred technology for generating energy from waste in India.

A decrease in priority of 0.17–0.1 for market establishment, which increases the priority of retention time from 0.83 to 0.9, will result in Gasification being the highest ranked alternative (see Fig. 3a). It is also worth highlighting that while the pair-wise comparisons of the alternatives with respect to the criteria have been carried out using judgement based on quantitative data from the literature, certain uncertainties still arises. For example, the establishment of the technologies is subjective given the availability of up-to-date information. Investigating the result based on AD's priority for establishment, highlights that gasification will be the preferred technology when AD's priority is less than 0.41 (see Fig. 3b); however, AD had a priority of 0.53. Gasification will also be the preferred technology if net output is given a priority weighting of at least 0.7, however this is a significant increase from the assigned priority of 0.06.

Table 2
Weighted supermatrix.

	Landfill	AD	Incin.	Pellet.	Gasific.	LHV	Net out.	Aux load	Pretreat.	Capex	Gen. cost	O&M	Emissions	Vol. red.	Establish.	Ret. time	Goal
Landfill	0.00	0.00	0.00	0.00	0.00	0.22	0.05	0.16	0.40	0.02	0.03	0.18	0.04	0.03	0.17	0.04	0.00
AD	0.00	0.00	0.00	0.00	0.00	0.40	0.03	0.01	0.09	0.16	0.12	0.08	0.34	0.11	0.53	0.15	0.00
Incineration	0.00	0.00	0.00	0.00	0.00	0.03	0.02	0.08	0.37	0.05	0.03	0.05	0.21	0.42	0.07	0.27	0.00
Pelletisation	0.00	0.00	0.00	0.00	0.00	0.13	0.21	0.04	0.04	0.05	0.25	0.01	0.05	0.06	0.17	0.27	0.00
Gasification	0.00	0.00	0.00	0.00	0.00	0.22	0.19	0.04	0.09	0.22	0.08	0.01	0.35	0.38	0.07	0.27	0.00
LHV	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07
Net output	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Auxiliary load	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Pretreatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.11
Capex	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.12
Generation cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
O&M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.01
Emissions	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.05
Volume reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.01
Establishment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.09
Retention time	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47
Goal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3
Limiting supermatrix.

	Landfill	AD	Incin.	Pellet.	Gasific.	LHV	Net out	Aux load	Pretreat.	Capex	Gen. cost	O&M	Emissions	Vol. red.	Establish.	Ret. time	Goal
Landfill	0.00	0.00	0.00	0.00	0.00	0.22	0.11	0.18	0.40	0.07	0.09	0.19	0.04	0.03	0.17	0.04	0.06
AD	0.00	0.00	0.00	0.00	0.00	0.40	0.12	0.09	0.09	0.28	0.14	0.11	0.34	0.11	0.53	0.15	0.12
Incineration	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.16	0.37	0.06	0.07	0.17	0.21	0.42	0.07	0.27	0.10
Pelletisation	0.00	0.00	0.00	0.00	0.00	0.13	0.17	0.04	0.04	0.09	0.16	0.03	0.05	0.06	0.17	0.27	0.09
Gasification	0.00	0.00	0.00	0.00	0.00	0.22	0.19	0.11	0.09	0.17	0.10	0.10	0.35	0.38	0.07	0.27	0.11
LHV	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Net output	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Auxiliary loads	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Pretreatment	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.20	0.00	0.00	0.06	0.20	0.00	0.00	0.00	0.00	0.06
Capex	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.06
Generation cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
O&M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.01
Emissions	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.20	0.00	0.00	0.03	0.10	0.00	0.00	0.00	0.00	0.03
Volume reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.10	0.00	0.00	0.00	0.00	0.01
Establishment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.05	0.00	0.00	0.00	0.00	0.00	0.07
Retention time	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Goal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Incineration will be the highest ranking technology if pre-treatment or O&M priorities' increase respectively from 0.55 to 0.85 or 0.08 to 0.57. Furthermore, if the priority of energy content is specified as less than 0.075 by the experts, rather than 0.33, incineration will be the highest ranked alternative for generating electricity from waste in India (see Fig. 4a and b).

6. Comparison study

To draw a comparison with another MCDM method, the analytical hierarchy process is applied to the same selection problem. In order to carry out an AHP study, the inner and outer dependencies are removed from the HANP model. The preferential rankings from the AHP are compared with the HANP results in Fig. 5, showing that in an AHP analysis, gasification is the preferred technology with a normalised ranking priority of 25%. For more information on the AHP the reader is referred elsewhere [28].

7. Results and discussion

The HANP analysis of technologies for generating electricity from MSW in India identifies anaerobic digestion as the preferred technology. However, this result will change depending on the decision framework adopted and variations in expert opinion. The results of the HANP and AHP studies are now examined and compared.

The HANP and AHP analyses produce similar trends in results; however, the ranking order of the technologies changes. As a result of the exclusion of inner and outer dependencies, the AHP model determines gasification to be the preferred technology with 25%, and AD is now in second place with a ranking priority of 23%. With AD's superior establishment in India, this change in ranking order is attributed primarily to the modelled dependency between capital cost and market establishment. Nevertheless, AD remains highly preferred in the AHP model. The preferential order of incineration, pelletisation and landfill remains the same among the two studies. In comparison to the HANP analysis, gasification and pelletisation increase respectively in preference from 23% to 25% and 19% to 20%, whereas landfill and AD decrease from 12% to 11% and 24% to 23%. An unexpected result is that pelletisation is low ranking in both analyses, even below incineration. This is attributed to the low volume reduction of waste, high operations cost and demand on a pre-treatment process.

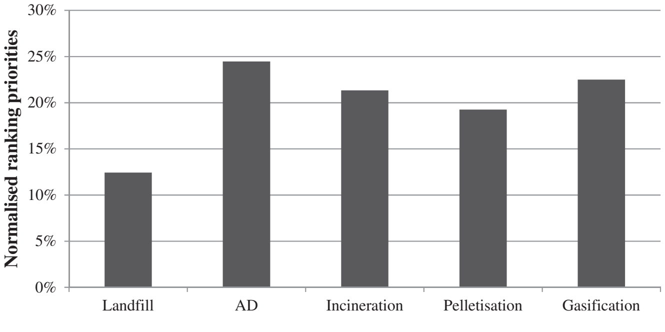

Fig. 2. Normalised ranking priorities showing the preference of each technological alternative for generating electricity from MSW in India.

The ranking order of alternatives in HANP and AHP analyses will change depending on the priority weightings. Given the uncertainty in how opinions may vary among experts in India, a sensitivity study has been carried out on the HANP result. Due to AD's retention time of several days and AD's and gasification's requirement on pre-treatment, an increase in priority on these criteria can result in AD, gasification or incineration being indicated as the preferred technology. Some of the alternative's priorities with respect to the criteria (judged by reviewing the literature) are also uncertain. In this study a value of 30% has been assumed for AD's market share of MSW treatment facilities in India and a value of 0% has been assumed for gasification. Considering that a number of gasification plants have been recently established or are in development in India, gasification could have a much higher priority against establishment. The sensitivity study shows that if AD's priority for market establishment fell from 0.53 to 0.41, gasification will be the preferred technology.

An advantage and strength of the HANP and AHP methods is that every aspect of the problem – known or unknown, tangible or intangible – can be incorporated into the decision making process. Thus uncertainty in the result will occur, however, sensitivity studies can be used to investigate how the ranking order might change with likely variations in priority weightings. Fuzzy logic can also be introduced to provide a potential range to priority weightings. The weightings are also likely to change depending on the proposed location for an energy recovery from waste plant. While the literature provides a good overview of the situation in India, site specific primary data should be used were possible to support MCDM models.

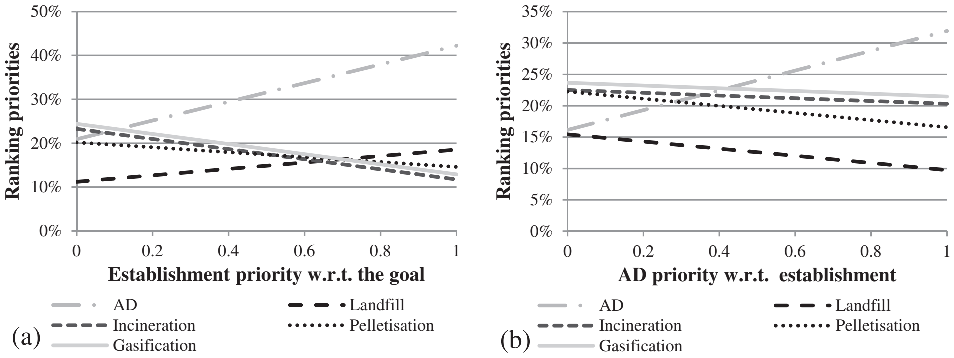

Fig. 3. Overall ranking of each alternative for a changing priority of (a) establishment with respect to the goal and (b) AD with respect to establishment.

The ANP process has been chosen for this study as it provides a suitable framework to address evaluation decision problems, rather than a design optimisation problem which would require goal programming, linear programming or similar. Although the AHP is the most established and popular MCDM method for evaluation decision problems, the HANP has been regarded as an improvement to the AHP model by several researchers. In this study we therefore fully evaluate the decision problem using HANP and AHP to investigate the selection problem at hand. Furthermore, structuring an ANP model within a hierarchy maintains the decomposition of a goal into individual assessment criteria, yet allows criteria dependencies to be modelled, which is one of the main drawbacks with AHP. Therefore the HANP approach enables the benefits of a network and hierarchy to be gained.

The potential use of HANP and its benefits for the management of MSW in India and elsewhere are substantial. Site, technology, capacity, and supplier selection are just a few of the critical decisions that need to be made in industry and are issues all too often not fully examined, resulting in projects failing. Though the HANP approach is complex, it provides a systematic structured approach to analysing specific decisions, thus improving organisation a reducing risk in decision making. While the AHP is easier to apply, HANP provides a more robust and reliable solution by capturing criteria dependencies. The outlined HANP methodology in this study for technology selection in the waste management sector should therefore be adopted by key decision makers in government authorities and industry. The authors consider that HANP will have an important role to play in ensuring sustainability in energy systems in India and other countries.

In future studies, additional criteria and alternatives may be considered in the context of the entire MSW supply chain, incorporating life cycle assessment and detailed simulation models of integrated waste disposal streams. Techniques such as the Delphi method can be used to obtain a census among a large group of experts and stakeholders. Additional evaluation criteria should also be incorporated into further studies to improve the model. For example, plant capacity could be included and the resulting dependencies on other criteria, such as capital cost, considered. The consulted experts in this study were given the opportunity to suggest additional criteria that they deemed important. Discussed criteria included social aspects (visual impact and public perception), ease of government monitoring and labour availability. These criteria are very site dependant and should be included in any reruns of this study for specific localities.

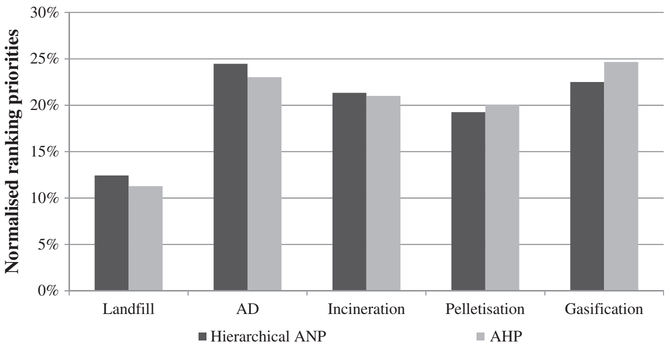

Fig. 5. Ranking priorities for each alternative. With 24%, AD is the preferred technology in the hierarchical ANP model. Gasification is the highest ranking technology in the AHP model with 25%.

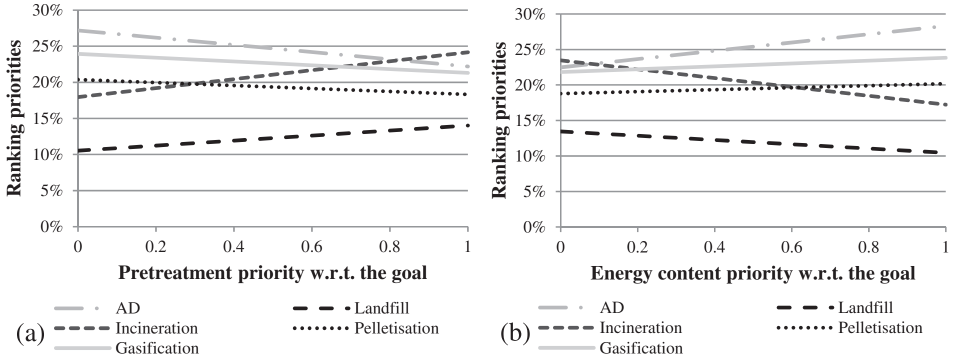

Fig. 4. Overall ranking priority of each alternative for changing (a) pre-treatment and (b) energy content priorities with respect to choosing the best technology for generating electricity from waste in India.

Applications of decision-making methods to case specific areas will be necessary in India as waste characteristics can vary substantially between cities, regions and states. Specific municipalities in India will also need to consider current social practices and public support in decision models. Reluctance for change in India has in particular restricted developments in the area of MSW management. In reality it will be a combination of technologies that will contribute towards reducing and providing energy services from MSW. However this study has shown which technologies should be prioritised, which may affect policies and has implications for investors and plant developers. The degree of preference also gives and indication to how much one technology should be employed in comparison to another in terms of installed capacity and suitable market shares.

8. Conclusion

This HANP study has compared five technologies to identify AD as the preferred technology for generating electricity from MSW in India. The results among two decision models, HANP and AHP, have show a normalised ranking priority of 23–25% for AD and gasification. Incineration ranks in third place with a preference of 21%.

Several recommendations arise from this study. Pelletisation is considered to be unfavourable for managing MSW in India as its ranking ranges from 19 to 20%. Landfill is shown to be extremely low ranking with a preference of 11–12%. The higher ranking of incineration is an unexpected result; historically incineration has been considered as an unfeasible option for India. We believe that there is a potential for modern-day state-of-the-art incineration plants in India to help achieve landfill rates comparable to western countries and therefore their adoption should be reconsidered. Although AD is indicated as the preferred technology, gasification is also a particularly promising technology. Further work is required to make recommendations based on social impacts as these are site specific issues. We conclude that a combination of AD and gasification for electricity generation from MSW should be the focus for municipalities, policy makers, entrepreneurs, investors and plant developers in India. We consider this to be a valuable and timely study for these stakeholders; India is rapidly developing and key infrastructure investments will soon be made, thus the opportunity for establishing the best technologies for managing MSW could be missed. Furthermore, the presented HANP methodology can be adopted by decision makers in the worldwide energy sector to minimise risk and ensure sustainability in project planning.

The effective utilisation of decision making tools, such as HANP, is becoming increasingly important to manage the growing complexity of sustainable energy systems. This study has illustrated how HANP can be applied to technology selection for energy recovery from waste. Furthermore we have demonstrated how HANP is preferable to other MCDM methods where criteria dependencies should be considered as the outcome of the decision may change. By providing a structured approach, the HANP method helps to identify all relevant criteria, facilitate the development of criteria weightings and incorporate dependencies between criteria attributes. Thus we have been able to make better and more informed recommendations for the use of alternative technologies in India for generating energy from MSW.

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